

**FINAL TECHNICAL REPORT  
FOR  
SCIENTIFIC DATA ANALYSIS  
AND SOFTWARE SUPPORT:  
GEODYNAMICS**

**NAS5-32352**

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## 1.0 OVERVIEW

This document will provide a summary of the Geophysics, Geodynamics, and Space Geodesy (GGSG) support that has been undertaken to support to the Laboratory for Terrestrial Physics and Laboratory for Hydrospheric Processes at NASA/GSFC under NASA contract NAS5-32352. The Raytheon ITSS team has delivered exemplary performance and achieved many significant technical milestones over the past 7 years on this contract.

Raytheon ITSS has established a partnership with NASA and GSFC that has spanned our 26-year history, and performance on this contract has been strong. Raytheon ITSS received ISO 9001 certification in 1998, and was selected as the winner of the 1999 Goddard Contractor Excellence Award in the category of large service organizations based partly on our performance on this contract.

Over the course of this contract, Raytheon ITSS has utilized the excellent services of several subcontractors:

- Sigma Research and Engineering Corporation (SRE) develops scientific instruments for aerospace applications. The company workforce is primarily focused on laser altimeter development at GSFC. SRE support to the LTP is growing rapidly due to their on-time delivery and the high quality of their hardware. The company is a minority owned small disadvantaged business, and is presently applying for 8A status.
- NVI, Inc. is a woman-owned small business with over seven years of experience in providing scientific and technical support to government and commercial customers. NVI is a world class participant in the field of VLBI. NVI personnel have been recognized for work on several projects within the LTP, including the 1989 Earthquake Response Team and the Crustal Dynamics Project awards.
- Herring Bay Geophysics (HBG) a one person company specializing in digital mapping, geomagnetics, remote sensing and planetary topography. HBG has supported the LTP for the past 16 years.

Our workforce on this contract had a remarkably low rate of employee turnover, 3.4%. This reflects our interest in the technical challenges we faced. By contrast, the national turnover rate for computer professionals exceeds 16%. This enabled the Raytheon team to provide uninterrupted support on the task assignments under this contract and we were able to man new tasks with seasoned professionals.

## **2.0 TECHNICAL PERFORMANCE SUMMARY**

The support on this contract centers on development of data analysis strategies, geodynamic models, and software codes to study four-dimensional geodynamic and oceanographic processes, as well as studies and mission support for near-Earth and interplanetary satellite missions. SRE had a subcontract to maintain the optical laboratory for the LTP, where instruments such as MOLA and GLAS are developed. NVI performed work on a Raytheon laser altimetry task through a subcontract, providing data analysis and final data production for distribution to users. HBG had a subcontract for specialized digital topography analysis and map generation.

Over the course of this contract, Raytheon ITSS staff have supported over 60 individual tasks. Some tasks have remained in place during this entire interval whereas others have been completed and were of shorter duration. Over the course of events, task numbers were changed to reflect changes in the character of the work or new funding sources. The description presented below will detail the technical accomplishments that have been achieved according to their science and technology areas. What will be shown is a brief overview of the progress that has been made in each of these investigative and software development areas.

Raytheon ITSS staff members have received many awards for their work on this contract, including GSFC Group Achievement Awards for TOPEX Precision Orbit Determination and the Joint Gravity Model One Team. NASA JPL gave the TOPEX/POSEIDON team a medal commemorating the completion of the primary mission and a Certificate of Appreciation. Raytheon ITSS has also received a Certificate of Appreciation from GSFC for its extensive support of the Shuttle Laser Altimeter Experiment.

### **2.1 Earth Gravity Field**

Raytheon ITSS has provided comprehensive support to the LTP in its study of the terrestrial gravity field for 30 years. Our analysts were actively involved with development of the JGM and EGM series of models and have performed error calibration tests for them. We analyzed satellite tracking, satellite altimetry, and ground-based data types, as well as their weighting in gravity solutions. RITSS has used data from dozens of satellites already flown and we have preliminarily studied the CHAMP, GRACE and GOCE missions that promise orders of magnitude improvement in the sensing of gravity signals from orbital altitudes.

### **2.2 Surface Gravity Data Analysis**

The gravity field analysts at RITSS worked in cooperation with NIMA to prepare surface gravimetry for inclusion in the gravity models and to develop techniques to accomplish high degree model recovery using these data. Our support has included ongoing improvement of the marine data set to produce a  $1^{\circ} \times 1^{\circ}$  file and development of topographic correction approaches for the continental data.

### **2.3 Time-Variable Gravity**

RITSS has developed state-of-the-art solutions for secular and decadal variations of the gravity, season changes, and geocenter variations. Our studies have employed data from a wide array of satellites, such as Starlette, Ajisai, Lageos 1 and 2, Etalon 1 and 2, and Stella. We have also assessed upcoming missions that will greatly improve the time and spatial resolution of these recoveries to design time varying gravity recovery solution approaches.

## **2.4 Non-Conservative Force Modeling**

Our analysts have lead or supported numerous investigations of non-conservative forces on spacecraft. Some involve detailed modeling of physical phenomena, through representational yet computationally efficient "macro models" to accommodate solar radiation pressure, planetary re-radiation, thermal imbalances, and neutral and charged particle drag. Others are "reduced dynamic" solutions where the data, along with covariance constraints, support the estimation of a large number of empirical parameters that account for the unmodeled residual accelerations.

## **2.5 GEOSAT Follow-On**

RITSS has analyzed GFO data since tracking began early in 1998. The limited functioning of its GPS system has forced a greater reliance on SLR and altimeter crossover data. Our analysts have enhanced and run the GEODYN program to generate a GFO-tuned gravity model and macro-model, as well as for determining optimal arc lengths, parameterization, and relative data weighting. Under this contract, Raytheon supplied the precision orbits being used to generate the prime mission products.

## **2.6 TOPEX/POSEIDON PODPS**

Raytheon developed the T/P PODPS and has used it to generate orbits with 2-3 cm radial accuracy since 1992. We were able to exceed mission requirements by a factor of at least four, by developing highly accurate gravity, tidal, and satellite-specific force models and by fully exploiting the excellent SLR and DORIS tracking data that are available. Over the past seven years had a 100% on-time delivery record for the orbits used to generate the prime mission data, with no deliveries having degraded orbit accuracy.

## **2.7 MGS And NEAR Missions**

Our analysts have performed extensive analyses on the data acquired by the MGS and NEAR missions. Herein, we applied our years of Earth gravity field modeling and POD activities to produce results, which were published in journals such as Science. These investigations have led to state-of-the-art topographic and gravity models for these solar system bodies.

## **2.8 Planetary And Interplanetary Studies**

RITSS performed many simulations of spacecraft orbiting solar system bodies to investigate geophysics and rotational dynamics deduced from Doppler and laser altimeter observations. We have done simulations and mission analyses for NEAR at asteroid 433 Eros, MUSES-C at 4660 Nereus, MESSENGER at the planet Mercury, and an orbiter at Jupiter's satellite Europa. We are currently analyzing the data collected during the rendezvous with Eros.

## **2.9 Future Mission Studies**

Raytheon ITSS performed a number of future mission studies and developed planning concepts for mission performance. This has included pre-launch simulations and covariance analysis for the TOPEX, GFO, and VCL missions for assessing orbit determination accuracy, instrument selection, error sources and their effect on mission science products. Our work, started with the ground-floor mission planning for TOPEX and VCL, and defined the anticipated level of orbit accuracy for these missions.

## **2.10 SLR Planning And Support**

RITSS has provided the GSFC Space Geodesy networks and Sensor Calibration Office with high level overviews of the scientific and engineering applications of SLR which have been included in the GSFC code 920.1 web information.

## **2.11 Global And Regional Plate Tectonics And Station Positioning**

Raytheon personnel have performed research on comparison and construction of combinations of geodetic solutions from SLR, GPS, DORIS, and VLBI, recovery of geocenter variations, regional tectonic deformation, and estimation of the vertical motion of tracking sites. These studies have resulted in more than 30 presentations at scientific meetings of the IAG, AGU and EGS and others. We have also supported both the WEGENER program, and the activities of both the Central Bureau and Analysis Working Group of the ILRS since their inception. As part of this support, RITSS personnel have validated SLR observations of ETALON, LAGEOS, Ajisai, TOPEX/Poseidon, Starlette, Stella, and GFZ-1, and have helped produce rapid orbit predictions for GFZ-1.

## **2.12 LAGEOS Investigations**

RITSS personnel have performed analysis of LAGEOS observations since launch in 1976. The evolution of the orbits of both LAGEOS I and II has been regularly monitored, and models for the satellites' motion are continuously improved. The procedure developed by the Raytheon uses the GEODYN/SOLVE system to reduce the SLR observations to determine the values and rates of change of position at all major stations in the SLR network, along with polar motion and length of day. The results have been submitted as the GSFC SLR contribution to the International Earth Rotation Service each year since the first solution.

## **2.13 Ocean Tides**

Raytheon orbit analysts fully participated with LTP personnel on the modeling and estimation of ocean tide parameters during development of the EGS96 gravity model. This work included a successful comparison between the tidal terms from EGS96 and those from the GEM-T3 derived tidal model PGS4846X. A comparison of the tidal resonant terms with results for altimeter-derived oceanographic tides also showed excellent agreement.

## **2.14 Geophysical Fluids Influences On Global Geodynamics**

RITSS has acquired global meteorological data sets from GSFC's Data Assimilation Office and the National Centers for Environmental Prediction, global runoff data from GSFC's Global Soil Wetness Project, and global sea-surface-height data from GSFC's Ocean Pathfinder office. We have processed these data sets and derived global hydrological data. We have also performed numerical integration of the results to determine the time series of global geodynamical parameters.

## **2.15 Sea Surface Data Analysis**

Raytheon ITSS has studied all aspects for determining the mean height of the sea surface including altimeter data analysis, computation of precise orbits, recomputation of orbits, assessment of orbit errors, determination of the marine geoid, and the analysis of temporal sea level variations. We have processed and analyzed the data from many ocean sensing satellites includ-

ing TOPEX/POSEIDON, GEOSAT, and ERS-1 and 2. Our analysts also developed a widely used on-line database for ocean altimetry (nearly 40 Gbytes in size) at GSFC under the Ocean Pathfinder project.

### **2.16 Dynamic Ocean Topography**

RITSS has made significant contributions to the GSFC-led investigations of DOT recovery for more than ten years. From the first successful attempts to exploit "direct" altimetry for this purpose to the state-of-the-art DOT fields recovered within the comprehensive geopotential solution that produced GEM-T3 through EGM96, we have performed analysis of altimeter data, optimal estimation of the DOT field, and testing and validation of the recovered DOT expansions using independent data and information (e.g., WOCE hydrography, POCM\_4B model products). RITSS also initiated investigation of Proudman functions to represent DOT, and developed a technique to map the marine geoid error onto the Proudman function basis.

### **2.17 Land Altimeter Studies**

Raytheon ITSS scientists developed algorithms for calculating topographic heights over land and rivers from satellite radar and shuttle laser altimetry. They created digital elevation maps of South America using the densest altimetry available from the geodetic missions of Geosat and ERS-1. They also used the repeat tracks from Geosat, and TOPEX to show the feasibility of monitoring large river basins such as the Amazon. They used the shuttle laser altimetry to develop algorithms that will be used to analyze VCL and GLAS overland returns.

### **2.18 VCL Support**

RITSS designed and started the development of the VCL Precision Geolocator Systems (VPGS) which continues at present in order to provide the precise orbital ephemeris information required for this mission. This system is based upon our highly successful PODPS, which has produced TOPEX orbits exceeding mission accuracy requirements since 1992. Our staff is using the GPS and SLR tracking data that will be the input to VPGS.

### **2.19 Shuttle Laser Altimeter Data Analysis**

Raytheon ITSS (and its subcontractor, NVI, Inc.) have provided valuable support to the first two flights of the Shuttle Laser Altimeter. The data were analyzed to produce data sets that provide laser altimetry elevations of high vertical accuracy that can be used for scientific purposes. The GEODYN program was used to simultaneously estimate geometric and dynamic parameters of the orbit and laser altimeter measurement modeling. This study showed the shuttle orbits to be accurate to within 1.5 m radial RMS and 8 m total position RMS.

### **2.20 Digital Topography**

RITSS and HBG have extensive experience with topographic instruments and the data that will be analyzed for this task assignment. This includes work on MOLA and SLA, and related work on VCL and ICESat. Our staff performed a wide range of engineering and scientific investigations pertaining to this analysis, such as precise orbit determination, footprint geolocation, attitude bias calibration, and waveform processing techniques.

## **2.21 ICESat Standard Science Data Products**

Raytheon has worked closely with the GLAS Science Team and its representatives over the past 4 years to define the 15 GLAS level 1 and level 2 standard products and design a software system that will create these products. We have had successful preliminary and critical design reviews, delivered version 0 of the GLAS Science Algorithm Software and are well on the way to creating version 1, which will have full functionality of all science processing based on ATBDs submitted to ESDIS.

Our involvement with the development of ICESat standard data products was unique. RITSS brought value-added insight to all the functions of this task including algorithm development, numerical simulation, and offered continuous support to the ICESat/GLAS Science Computing Facility and Science Team.

## **2.22 Polar Ice Science Using Altimetry**

RITSS performed ice field related work on ERS-1 and 2, TOPEX, MGS, and GFO altimeter missions, all of which acquired significant data sets over ice. Our analysts have developed algorithms for the correction of mistracking, surface slope induced errors, atmospheric refraction and tides. In addition, our extensive involvement with GLAS allowed us to define scientifically important strategies to be employed from the altimetry data products that this satellite will produce.

## **2.23 MOLA Laser Altimetry**

Raytheon ITSS assessed MOLA elevation measurements of the north and south polar regions of Mars. Our analysts developed a first version of the software based upon our radar DBMS system to create a database of the MOLA measurements and to plot profiles over topographic images from this database. Code was also developed to generate maps and profiles and to deduce surface slope and ice flow direction. We are continuing our attempts to model the surface shape of the North Polar ice cap.

## **2.24 MOLA2 Flight Operations Activities**

RITSS personnel have been performing the MOLA2 flight operations since its inception. We monitor instrument health and performance, monitor the MGS spacecraft temperature, develop command sequences in response to Science Team and Instrument Team requests, insure that command sequences are properly implemented, retrieve MOLA2 telemetry, retrieve SPICE Kernel files, and generate a MOLA2 daily status report.

## **2.25 TOPEX/JASON Altimeter Performance Analysis**

RITSS support has played an active and wide ranging role in altimeter performance assessment and verification. Prior to launch, our software development was instrumental in establishing an altimeter performance database and in evaluating algorithms being developed for the TOPEX altimeter. After launch RITSS placed the software system under configuration control, enhanced its capabilities, adopted IDL for plotting, and continually provides altimeter performance assessment products.

### **2.26 GEOSAT Follow-On (GFO) Radar Altimeter Instrument Calibration**

Raytheon personnel, working closely with NASA, have been directly involved with all aspects of satellite radar altimetry performance monitoring and calibration.

### **2.27 Laser Remote Sensing**

SRE personnel have worked in the areas needed to support GLAS and the other laser remote sensing projects. Staff engineers have proven success as demonstrated by designing, developing, building, testing and delivering space hardware for several previous missions including the Mars Observer Laser Altimeter. In addition, they have already completed much of the work on GLAS, and have begun analysis of the Europa and Mercury missions.

### **2.28 GEODYN**

Raytheon personnel have been developing the GEODYN program for decades. RITSS provided extensive support in orbit dynamics, Earth sciences, statistical estimation, and mathematical modeling and computational problems. Recent areas of development in GEODYN include 2-way laser altimeter modeling, dynamic crossover pre-processing and analysis, and sea surface height evaluation using Proudman functions.

Our analysts have enhanced our codes for data pre-processing, GEODYN and SOLVE, and post-GEODYN analysis software that is required for future missions. We developed the PODPS, as well as our work with MGS, GFO, OOD, VDC and other missions and instruments. We are also developed codes to support mission-specific data types such as ramped Doppler, altimetry dynamic crossovers, and GPS formats. Our successes in these areas have allowed GSFC to efficiently adapt existing software to support future missions.

### **2.29 Microaltimeter Data Analysis And Display**

RITSS wrote the GRAPES software. In addition to writing GRAPES, our analysts have developed specific laser altimeter data processing codes for GLAS, TOPEX and other missions.

### 3.0 SCHEDULE COMPLIANCE

Several aspects of our ICESat support have been heavily schedule driven in order to have the processing system and Science Computer Facility, SCF, visualization and DBMS operational six months before launch. The milestones were defined by starting with launch and working backwards. Initially a July 2002 launch date was expected and the schedule had to be compressed to meet the revised July 2001 date. The Raytheon ITSS team records speaks for itself. The following milestones have been met under the existing contract to keep all systems on schedule for completion and checkout by launch:

- Definition of GLAS standard data products, 2/00
- ATBD version 1 delivery, 7/99
- PDR and CDR, architectural and detailed design for all aspects of ICESat Science Investigator Processing System, ISIPS 11/99
- CDR for the main and remote SCF visualization and DBMS 1/18/00
- Version 0 of ISIPS, 7/99
- Release 1 of SCF visualization software 3/00
- Hardware requirement definition for SCF (includes ISIPS) 11/99
- First set of hardware ordered for SCF (includes ISIPS) 1/00
- Facility plan for ISIPS 11/99

GFO Medium-precision Orbit Ephemeris (MOE) files are currently produced at GSFC by Raytheon ITSS personnel within 24 hours for use on the GFO Intermediate Geophysical Data Record (IGDR). The MOEs are exported daily over the normal workweek. The MOE is based on SLR tracking. Each workday processing begins at about 8:30 AM (EST) when the SLR data becomes available for tracking over the previous day, and following import of solar flux and earth orientation parameter data. At 1:00 PM of that day, Doppler tracking data is included in the orbit solution if available. Over the course of the day, several candidate orbits are produced and evaluated based on SLR data fits, orbit overlap differences, and adjusted parameter values. The best candidate orbit is exported before the close-of-business that day, typically around 4:00 PM. For quality control, two documents are exported along with the MOE: an orbit quality statistics summary and operator log. Under off-nominal conditions, when there is little or no SLR tracking, or there is a satellite maneuver, delivery of the orbit is postponed until sufficient tracking becomes available, usually by the next day. GFO Precise Orbit Ephemeris (POE) files are produced and delivered on a best-effort basis, typically 1-2 months following MOE delivery.

Raytheon also developed the TOPEX PODPS System within highly constrained mission schedule and cost objectives. The initial system supported data validation and verification activities and required an upgrade to support actual mission operations. This required tuning the models with actual TOPEX data, testing performance using orbit and in situ information, and verifying that the maximum performance was delivered for operational purposes within a 6-month period. All performance, cost, and schedule objectives were met. A high level of performance continues to be delivered for the operational phase of the TOPEX mission, and we have met the scheduled delivery of over 275 orbits.

In a similar fashion, all of the Altimeter Pathfinder development was accomplished in an environment of very tight budget and time constraints. The system was developed and has met its design goals within schedule and cost constraints, while coping with significant budgetary downsizing.